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Assessing woody vegetation trends in Sahelian drylands using MODIS based seasonal metrics

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Abstract

Woody plants play a major role for the resilience of drylands and in peoples' livelihoods. However, due to their scattered distribution, quantifying and monitoring woody cover over space and time is challenging. We develop a phenology driven model and train/validate MODIS (MCD43A4, 500 m) derived metrics with 178 ground observations from Niger, Senegal and Mali to estimate woody cover trends from 2000 to 2014 over the entire Sahel. The annual woody cover estimation at 500 m scale is fairly accurate with an RMSE of 4.3 (woody cover %) and r^2 = 0.74. Over the 15 year period we observed an average increase of 1.7 (±5.0) woody cover (%) with large spatial differences: No clear change can be observed in densely populated areas (0.2 ±4.2), whereas a positive change is seen in sparsely populated areas (2.1 ±5.2). Woody cover is generally stable in cropland areas (0.9 ±4.6), reflecting the protective management of parkland trees by the farmers. Positive changes are observed in savannas (2.5 ±5.4) and woodland areas (3.9 ±7.3). The major pattern of woody cover change reveals strong increases in the sparsely populated Sahel zones of eastern Senegal, western Mali and central Chad, but a decreasing trend is observed in the densely populated western parts of Senegal, northern Nigeria, Sudan and southwestern Niger. This decrease is often local and limited to woodlands, being an indication of ongoing expansion of cultivated areas and selective logging. We show that an overall positive trend is found in areas of low anthropogenic pressure demonstrating the potential of these ecosystems to provide services such as carbon storage, if not over-utilized. Taken together, our results provide an unprecedented synthesis of woody cover dynamics in the Sahel, and point to land use and human population density as important drivers, however only partially and locally offsetting a general post-drought increase.

Introduction

Changes in woody plant cover, woody biomass, carbon stocks and productivity of woody vegetation have been at the center of discussions of environmental trends in Sahel since the severe droughts of the 1970s and 1980s. During these drought years, greatly reduced woody cover was widely reported, and this was regarded as an indication of ongoing land degradation/desertification, caused by the droughts, by savanna clearing to expand cropped lands, or by increasing demand for charcoal and wood-fuel in urban centers (Kandji *et al*. 2006; Tappan *et al*., 2004; Vincke *et al*., 2010). While examples of continuation of this downward trend in woody cover have been reported (e.g. Gonzalez *et al*, 2012; Ichaou, 2009; Wezel and Lykke, 2006), examples of reversed trends have also been documented (Rasmussen *et al*, 2001; Hiernaux *et al*. 2009a, Brandt *et al*., 2015). However, these studies are all conducted at the local scale and refer to relatively small parts of the Sahel, and comprehensive regional wide assessments are rare. Large scale studies focus on the so-called 'greening of the Sahel' (Fensholt *et al*., 2012), but the methods and data-sources used to document this greening do not allow separation of the effects of changes in the woody and herbaceous vegetation (Mbow *et al*., 2015). Only recently Kaptué *et al* (2015) suggested a methodology to attribute satellite based trends to woody or herbaceous components. As regards carbon stocks, it has recently been argued that drylands, such as the Sahel, actually control variability and trends in vegetation carbon storage at global scale (Ahlström *et al*., 2015), yet the role of Sahelian woody cover change in the global carbon sink is unclear. While annual herbaceous vegetation that is dominant in the Sahel impact inter-annual variability, the long-living woody stratum is found to contribute more to long-term trends in vegetation productivity, but magnitude and spatial patterns are not well studied (Brandt *et al*., 2015).

Recent progress has been made in assessing forest canopy cover changes at global scale and in the tropics from various Earth Observation (EO) systems (Margono *et al*., 2014; Kim *et al*., 2014; Hansen *et al*., 2013; Broich *et al*., 2011a; Broich *et al*., 2011b). However, current EO based methods are developed to estimate woody cover in closed canopy forest areas, and are not suited to detect the scattered canopies of bushes, shrubs and small trees in dryland savannas like the Sahel (Hansen *et al*., 2016; Gessner *et al*., 2013; Hansen *et al*., 2002). At the present state, all available assessments of dryland woody cover remain snapshots in time (Brandt et al., 2016; Kaptué *et al*., 2015; Karlson et al., 2015; Wu et al., 2013). Moreover, Dynamic Global Vegetation Models (DGVM) do not adequately capture drylands woody vegetation dynamics due to limitations in parametrization and representation of savanna ecosystems (Ahlström *et al*., 2015) as a balanced coexistence of herbaceous and woody plants. Although the need for a large scale study on trends and changes in woody cover in Sahel is evident, the limitations of high spatial resolution EO data (high prices, data availability and volumes, being spatio-temporal snapshots in a highly dynamic ecosystem) reduce their usability for continuous change analysis at the scale of the Sahel. Knowing these shortcomings, approaches based on plant phenology and NDVI seasonal metrics (representing the intra-annual dynamics of vegetation greenness) derived from low spatial but high temporal resolution EO time series (Broich et al., 2015) have proven to be a viable alternative quantification of dryland woody cover (Brandt *et al*., 2016; Horion *et al*., 2014). However, trend assessments based on coarse spatial resolution data also require an adequate number of ground observations over several years being in spatial correspondence with the satellite data. These continuous records of field data are needed to train and validate the phenology driven models and currently limit the number of studies available on this topic. Moreover inter-annual variations in plant phenology and leaf density impact on EO time series derived trends, adding additional challenges to change assessments (Broich et al., 2014).

Recently, Brandt *et al*. (2016) suggested a phenology based method to produce a static woody cover map for Sahel. The method is based on observed differences in the phenophases of dryland woody vegetation and herbaceous plants, used to estimate the dry season foliage density as a proxy for woody cover. Here we expand on this approach to map changes in woody cover for the same study area, thereby clarifying the role of woody vegetation in environmental change taking place in the region. Our specific aims are (1) to separate woody cover trends from herbaceous cover and rainfall related fluctuations, (2) to estimate recent woody cover trends in the Sahel (2000-2014), and (3), to assess the pattern of trends in relation to human population density and land use.

Materials and Methods

This study used MODIS (Moderate Resolution Imaging Spectroradiometer) satellite imagery (MCD43A4 at 500 m spatial and 8 day temporal scale) and 178 ground-based woody cover measurements (77 sites) over the period 2000-2015. We applied dry season NDVI metrics to predict woody cover, based on the assumption that only trees and shrubs have active photosynthesis during the dry season whereas annual herbaceous wilt towards the end of the wet season (Fig. 1) (Brandt et al., 2016). *In situ* woody cover was adjusted to site specific dry season foliage density (using species specific phenology characterized by a monthly norm of foliage density (Hiernaux et al., 1994)) to match with the with dry season NDVI data. Furthermore, if a statistically significant relationship existed between wet season NDVI (a proxy for rainfall) and following mean dry season NDVI, we assume that inter-annual fluctuations in foliage density are not caused by changes in woody populations but by rainfall conditions. In this case, the wet season NDVI peak was used to correct the dry season NDVI. The final satellite-based regression model predicts woody cover for the Sahel by dividing the predicted dry season foliage density by the weighted mean of woody species foliage density during the dry season. Annual maps were produced and significant trends analyzed in relation to land cover and human population data.

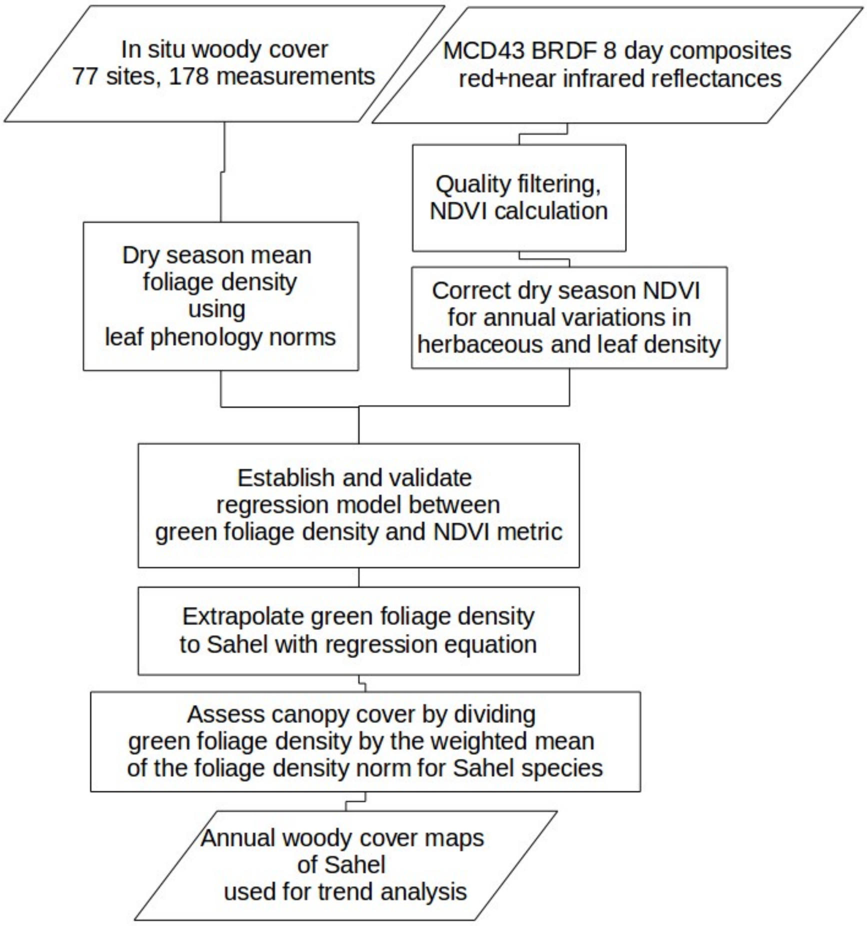

Figure 1 Methodological work-flow including ground observations and EO data for assessing changes in the woody cover of the Sahel.

Study area

The Sahel belt consist of three major bioclimate zones (Fig. 2), delineated by rainfall isohyets: the northern Sahel (Saharo-Sahelian), the central Sahel (Sahelian proper) and the southern Sahel (Sudano-Sahelian) (Le Houerou, 1980). According to Brandt *et al*. (2016), the woody canopy cover of the open tree and shrub savannas averages approximately 7% (at 1 km scale) across the Sahel and is increasing with long-term mean rainfall from 2 to 15% from northern to southern Sahel. Woody species distribution also changes along the north-south rainfall gradient (Table 1). The herbaceous vegetation of the entire Sahel belt consists mainly of annual herbaceous species (Le Houerou, 1980). Our field sites are distributed over the sparsely populated regions of eastern Senegal (24 sites) (Diouf *et al*., 2015), the Gourma in eastern Mali (21 sites) (Hiernaux *et al*., 2009a), and the Fakara in southwestern Niger (32 sites) (Hiernaux *et al*., 2009b). The Senegalese sites cover a gradient from the sparsely vegetated north to the more densely vegetated south. In Mali, the sites are located in the northern and central Sahel, all with a generally low woody cover around 3%, except on fine textured soils in lowlands. The land use of the Senegalese and Malian sites are exclusively rangelands and human influence is limited to grazing, cutting, and logging. In Niger, the field sites are located at the transition between central and southern Sahel and the landscape is a highly fragmented agro-pastoral land, with some sites being located on extensively cultivated land with frequent shifts between crop and fallow and some sites on permanently cultivated land (Hiernaux *et al*., 2009b). Several Niger sites cover rangeland and tiger bush areas on more shallow soils (Hiernaux *et al*., 1999).

Table 1 Dominance distribution of iconic woody species across the bioclimatic sub-zones of the Sahel (species named after Arbonnier, 2004) with indication of the foliage phenology: evergreen renewing foliage at the onset of the dry or wet season, deciduous with foliage duration either short, medium, long or reversed with foliage only during the dry season. A complete table with potentially dominant species is found in the supplementary material.

Sahel bioclimatic zones		**Northern**			**Central**			**Southern**		**Phenological behavior**
isohyets (mm)	150			300			500		700	
woody cover (%)		2			6			15		
Salvadora persica	*	*								Evergreen (dry season)
Maerua crassifolia	*	*	*							Evergreen (dry season)
Euphorbia balsamifera	*	*	*	*	*					Short deciduous
Acacia tortilis raddiana	*	*	*	*	*					Long deciduous
Acacia ehrenbergiana	*	*	*	*	*					Medium deciduous
Commiphora africana	*	*	*	*	*	*				Short deciduous
Leptadenia pyrotechnica	*	*	*	*	*	*				Evergreen (dry season)
Calotropis procera	*	*	*	*	*	*	*			Evergreen (dry season)
Balanites aegyptiaca	*	*	*	*	*	*	*	*	*	Evergreen (dry season)
Ziziphus mauritiana	*	*	*	*	*	*	*	*	*	Medium deciduous
Acacia nilotica	*	*	*	*	*	*	*	*	*	Long deciduous
Boscia senegalensis	*	*	*	*	*	*	*	*	*	Evergreen (dry season)
Acacia seyal		*	*	*	*	*	*	*	*	Short deciduous
Combretum micranthum			*	*	*	*	*	*	*	Short deciduous
Faidherbia albida			*	*	*	*	*	*	*	Reversed deciduous
Guiera senegalensis			*	*	*	*	*	*	*	Long deciduous
Acacia senegal			*	*	*	*	*	*	*	Short deciduous
Piliostigma reticulatum				*	*	*	*	*	*	Evergreen (wet season)
Pterocarpus lucens				*	*	*	*	*	*	Medium deciduous
Anogeissus leiocarpus				*	*	*	*	*	*	Medium deciduous
Combretum glutinosum					*	*	*	*	*	Evergreen (wet season)
Adansonia digitate					*	*	*	*	*	Long deciduous
Sclerocarya birrea					*	*	*	*	*	Medium deciduous
Pterocarpus erinaceus								*	*	Medium deciduous
Prosopis Africana								*	*	Long deciduous
Bombax costatum								*	*	Short deciduous
Vitellaria paradoxa								*	*	Evergreen (wet season)

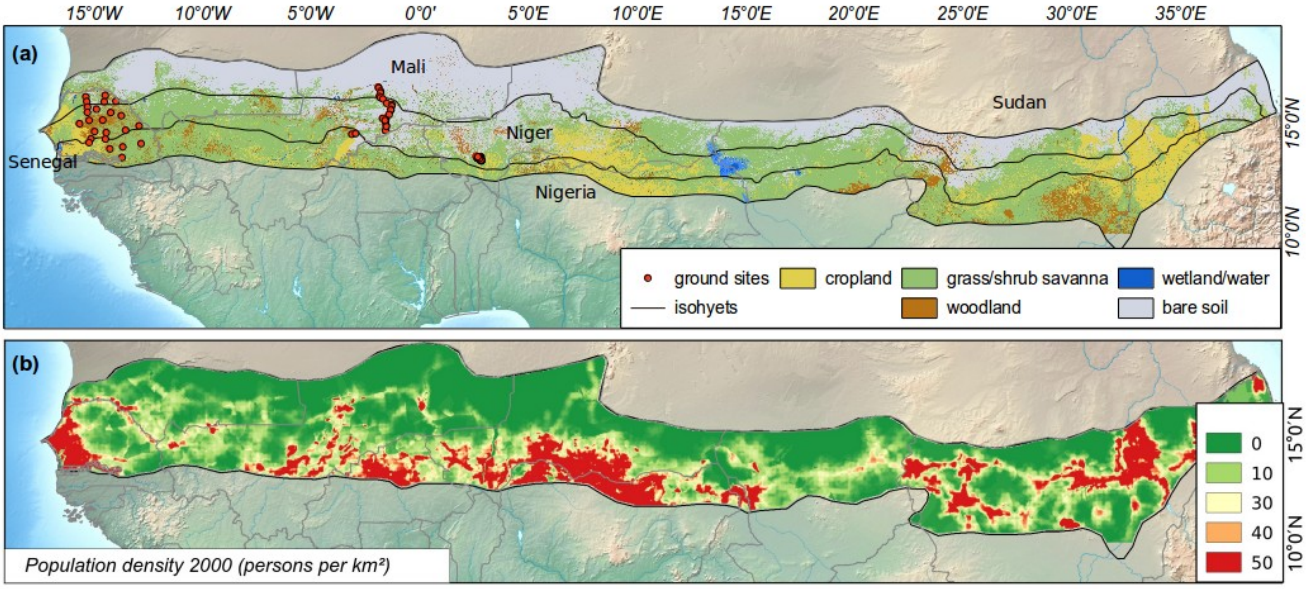

Figure 2 Overview of the Sahel belt. (a) Location of the ground monitoring sites in Senegal, the Gourma region in Mali and southwestern Niger. Rainfall delineations (150-300 mm, 300-500 mm, 500-700 mm) are based on annual average precipitation (African Rainfall Climatology Version 2 1983–2013). Land cover is Globeland30 aggregated to 500 m. (b) Population density map is based on the African Population Database (Nelson, 2004) for the year 2000.

Earth Observation data

This study uses MODIS MCD43A4, a BRDF (Bidirectional Reflectance Distribution Function) corrected reflectance product available at a 500 m spatial resolution (Schaaf et al., 2002). Each 8 day composite selects the highest quality value from both Aqua (overpass time 13 p.m.) and Terra (10 a.m.) satellites to minimize the influence of clouds. NDVI was calculated using the red and near-infrared surface reflectance bands. NDVI has been shown to be a function of canopy cover, soil color and moisture, leaf color, foliage density and canopy depth, and is a widely used measure of chlorophyll abundance (Myneni and Hall, 1995). Moreover, NDVI integrated or averaged over time serves as a proxy for net primary production (NPP) in drylands (Prince, 1991). Only pixels flagged as high quality (full BRDF inversion) were kept and all other pixels masked (in total 9% of the pixels between October and June were masked). We worked on non-filled and non-smoothed time series to avoid unrealistic fill values, assuming that keeping only the remaining high quality pixels provide a valid estimation of dry season reflectance.

Very high spatial resolution (VHR) satellite images were acquired from NASA covering all field sites for the period 2003 to 2015. Images are from the Geoeye 1, Quickbird 2 and Worldview 1&2 satellites and the spatial resolution is around 50 cm for the panchromatic band and 2 m for the multi-spectral bands. The digital numbers were converted to top of atmosphere reflectance (using Orfeo toolbox) and false color composites (near infrared, red, green) were pan-sharpened to a 50 cm resolution. The images are used for visual interpretation and illustration of trends detected in MODIS time series as a quantitative implementation of VHR data is outside the scope of this study.

Population, rainfall and land cover data

Additional datasets were used to investigate relations for underlying causes of vegetation trends. Gridded data on population density were downloaded from the African Population Database (Nelson, 2004) for the year 2000 in 2.5 km resolution and resampled to 500 m with a bicubic interpolation method, which provides smoother results than bilinear and cubic interpolations and is well suited for continuous data. These grids give a rough estimate on persons per km^2 and were derived from census data, transportation networks and the location of urban centers. We assume that grids with a population density higher 30 persons per km^2 are densely populated and grids with less than 10 persons per km^2 are referred to as sparsely populated. Globeland30 was used as land cover data (Chen *et al.*, 2015). It is derived from Landsat and globally available at 30 m resolution, for this study aggregated to 500 m with the nearest neighbor method. Annual precipitation was derived from TAMSAT (Tropical Application of Meteorology using SATellite), a Meteosat based rainfall dataset. TAMSAT is available at 0.0375° spatial resolution and estimates rainfall via thermal infra-red reflectances from the top of convective storm clouds (Tarnavsky, 2014).

Ground measurements of woody cover

Woody cover in this study is defined as the projection of the woody canopies on the ground surface, capturing the canopy cover of all woody phanerophytes, regardless of size. We included 178 *in situ* measurements between 2000 and 2015 (not continuous at all sites) measured at 77 ground sites located in the western part of the Sahel, in Senegal, Mali (Gourma) and Niger (Fakara). Each site is a 1x1 km plot within a homogeneous area of 3x3 km, except in Niger, where the sites are smaller in size (300x100 m) but selected in larger units. At each site, the height, basal and crown diameter were measured for all woody species (trees, shrubs and bushes) within four circular plots (up to 1 ha size) along a 1 km transect line. Outputs of the measurements are the mean woody cover for each site as well as the contribution of each woody species to the total cover (Hiernaux *et al*. 2009a).

Adjusting the in situ woody cover and dry season NDVI

The dry season NDVI does not directly measure woody canopy cover but the mean foliage density during the dry season, which is used to derive the woody cover (Brandt *et al.*, 2016). Indeed, woody species have different phenological behavior with a varying foliage density between October and June, depending on the leaf seasonality of each species (Table 1). Evergreen species (e.g. *Combretum glutinosum*) for example keep their leaves throughout the year, whereas deciduous species (e.g. *Pterocarpus lucens*) shed their leaves early in the dry season. In the Sahel, six different phenotypes (short-, medium-, long-, inversed-deciduous, 2 types of evergreen) have been identified and characterized by norms of foliage densities over time (Table 1) (Hiernaux et al., 1994). The mean foliage density from October to June was calculated for each site, which is an average weighted by the contribution (%) of each species to the woody canopy cover i.e. the norm of foliage density per unit canopy over time. This method adjusts the *in situ* woody cover to the percentage of green foliage mass during the dry season improving the relation with the dry season NDVI (Fig. 3).

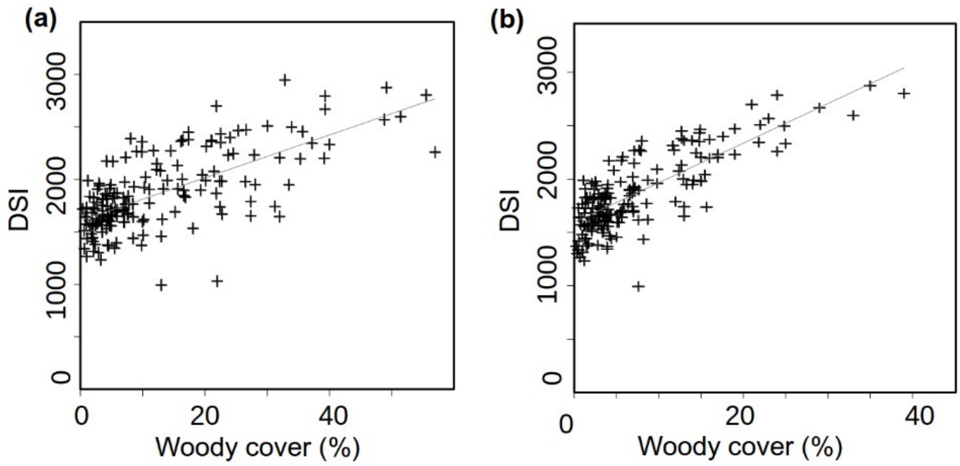

Figure 3 Adjusting *in situ* woody cover: (a) DSI (dry season NDVI corrected for inter-annual fluctuations) is compared against the woody cover measurements before and (b), after adjusting the *in situ* woody cover to the dry season foliage density.

Woody population trends and dynamics

When analyzing woody plant trends, two time scales must be distinguished: (1) Inter-annual fluctuations in woody plant leaf mass: These changes vary greatly between years depending on the water balance but also human management, like pruning and burning (Hiernaux *et al*., 1994). The variations in density of leaves within the canopy are also accompanied by changes in leaf phenology, which is affected by local (soil fertility, plant density, pruning-burning treatments) and time dependent effects (water balance conditions) (Broich et al., 2014; Hiernaux *et al*., 1994). Deciduous species can keep their leaves longer in a given year, renew their leaves earlier or some can even become evergreen for a year. These processes contribute to inter-annual fluctuations of the dry season NDVI, which is considered as 'noise' in this study. (2) Woody population dynamics at a multi-annual time scale: Knowing that the life cycle of most woody plants spans over several decades, a time step of approximately 5 years is the minimum to capture the fastest population increases. The woody population, in density, basal area, and canopy cover does not change fast and abruptly, unless it decreases rapidly, following fires, extended clearing, cutting or massive dying as it happened in the Sahel in 1984-85 following two years of drought. The aim of this study is to capture the second scale and attenuate the short year-to-year fluctuations not related to woody population dynamics.

Using dry season NDVI for woody cover estimation

We calculate a dry season index (DSI) serving as a proxy for woody cover and consisting of three components:

(1) *The mean dry season NDVI*: Given that no annual herbaceous vegetation is green during this period, the dry season NDVI was calculated averaging all values between the onset of the dry season (EOS) and the start of the wet season (SOS). To mitigate annual fluctuations caused by rainfall and phenology changes, the same EOS, October 8th (DOY 281), and SOS dates, June 9th of the following year (DOY 161), were used for each year and pixel. Although the wet season may start later (end of June), we chose the earlier date to avoid excessive influence by cloud cover, which is common in Sahel during this time (Fensholt et al., 2007).

(2) *The wet season maximum NDVI*: In order to account for the fluctuations of dry season NDVI due to variations in woody foliage densities and interferences by variable straws and litter masses (Tagesson *et al*., 2015), the wet season NDVI peak was calculated for each growing season, serving as a proxy for the rainfall/water balance conditions and thus the herbaceous and woody leaf mass of the corresponding year (Diouf *et al*., 2015). To reduce the influence from missing and bad quality values during the wet season, a running mean over 5 images (each an 8 day composite) was applied to smooth the time series from June to October. If a significant ($p<0.05$) relationship between the peak NDVI and the following dry season average NDVI was observed, the mean dry season NDVI was corrected for these variations. Here, the coefficients of the regression between wet and dry season were used to predict the dry season from wet season values (Bégué *et al*. 2011). A predicted dry season NDVI was calculated for each year using the peak of the wet season and the regression

equation. This predicted dry season value (which is assumed to be solely driven by rainfall) was then subtracted from a reference season , which was predicted with the mean peak over 15 years. The result was added to the dry season NDVI for a given year, to remove the fluctuations caused by rainfall and extract the NDVI driven woody population change.

(3) *Base level*: The mean annual minimum NDVI value over 15 years was calculated, being a proxy for the pixel's permanent leaf cover without any green herbaceous influence. By including the mean base level, singular major events, e.g. a bush fire but also remaining sensor noise and data gaps caused by clouds, are attenuated. DSI is calculated as follows (where DS is short for dry season):

$$DSI = \left(DS\,actual + \left(DS\,reference - DS\,predicted \right) + mean\,DS\,baselevel \right) / 2 \quad \text{(E1)}$$

Finally, a running mean over 2 years (averaging the current and the previous year) was applied to the DSI to reduce uncertainties caused by the masking of bad quality values leading to gaps which can influence the outcome of a single year. Hence, the results become more stable and less affected by data uncertainties and were found to significantly increase the correlation with annual *in situ* observations. Moreover, the water balance over several years impacts on the woody plant production (carbohydrate reserves, root system and woody architecture). In a final step, a regression model was established between 178 dry season mean foliage densities (derived from measured canopy cover and specific phenological norms) and DSI (2 year average values corrected for annual fluctuations) of the corresponding pixels and year. Polygons were drawn over the ground sites and the values of the pixels contained were averaged. To improve the normal distribution, logarithmic transformations of the variables were applied before building the model (Zandler *et al*., 2015). The derived coefficients (slope s, intercept i) are used to predict the woody cover from DSI:

$$predicted\,woody\,cover = \frac{\left(\log\left(DSI \right) * s - i \right)^2 * CF}{b} \quad \text{(E2)}$$

where *CF* is an empirical correction factor for the logarithmic back-transformation (Zandler et al., 2015) and *b* is the Sahelian norm for dry season foliage density to derive woody cover from dry season mean NDVI. The Sahel dry season foliage density (0.63) was calculated by estimating the relative contribution of the 6 woody species phenotypes within three bioclimatic zones and then weight them by mean canopy cover within each zone (Brandt et al., 2016).

Trend analysis (Theil Sen slope)

A Theil Sen slope trend analysis was applied to detect trends and changes in woody cover. Sen's slope is a non-parametric linear regression selecting the median slope, being robust against outliers (Hoaglin *et al*. 1983). Although the time period is rather short, a trend analysis over 15 years is expected to detect progressive and subtle changes, which are typical for changes in woody populations. Singular impact of contaminated pixels are considered as outliers and noise. Small scale changes (e.g. thinning woody plants in a stand or clearance of single fields within a pixel) play a minor role at a 500 m scale. The absolute change (linear increment or decrement) in percent woody cover was calculated by multiplication of the slope with the number of years. NDVI is prone to noise in very sparsely vegetated landscapes, hence, all areas with a mean woody cover lower than 2% were masked in the trend map. Moreover, wetlands, water bodies, irrigated and flooded areas were masked using both Globeland30 and the ESA LC CCI land cover masks. The remaining significant trends ($p<0.05$) of the EO based woody cover estimations are analyzed at Sahel and country scales, and with zoom on areas in Senegal, Niger, Mali and Nigeria. Being a highly heterogeneous ecosystem, the breakdown from Sahel scale to local close-ups is essential for improved interpretation of drivers.

Results

Estimating woody cover at annual scale

The MODIS based predicted woody cover (from DSI as derived from EO data) is able to reproduce the 178 corrected *in situ* woody cover measurements fairly accurate at the annual scale with r^2 of 0.74 (slope 0.89, offset 2.0, p<0.01) and RMSE of 4.34% woody cover (Fig. 4). The linear trends of 19 field sites (providing continuous data) are in line with the MODIS based predicted woody cover trends (r^2 of 0.73) and trends are predominantly positive (Fig. 4b).

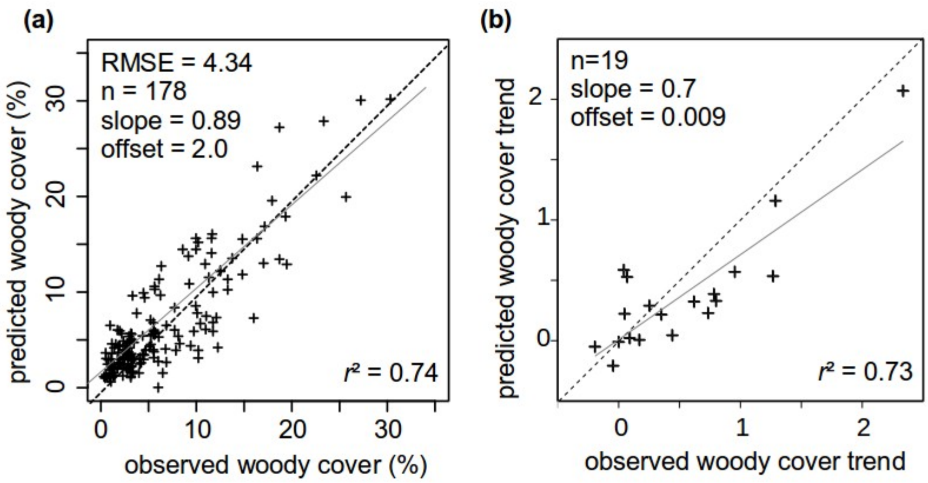

Figure 4 Woody cover predictions: **(a)** Predicted woody cover is compared with observed woody cover for all 77 ground sites and 178 *in situ* woody cover measurements. (b) Linear trends in woody cover (woody cover (%) year^{-1}) from 19 field sites in Senegal are compared against the trends predicted from MODIS dry season NDVI (only 19 of the 77 field sites provide continuous data and can be used for trend analysis).

T**able 2** Mean woody cover (%) and significant ($p<0.05$) change in woody cover (%) (2000-2014), averaged by countries and classes. The mean woody cover per class (first column) is shown in brackets. Mean and standard deviation are given. Only the areas inside of the Sahel belt are considered. Striking differences can be found between densely and sparsely populated areas.

	Sahel	**Senegal**	**Mali**	**Burkina Faso**	**Niger**	**Chad**	**Nigeria**	**Sudan**
Mean woody cover (%)	7.3 ±8.4	20.4 ±14.8	6.4 ±8.3	8.5 ±5.9	3.6 ±3.2	7.2 ±6.1	11.8 ±6.4	8.7 ±7.7
Change in woody cover (%)								
Entire area (mean cover 8%)	1.7 ±5.0	7.2 ±7.3	3.5 ±5.0	1.2 ±3.2	-0.3 ±1.4	1.4 ±3.1	-0.8 ±3.8	1.1±4.4
< 10 persons per km² (mean canopy cover 6%)	2.1 ±5.2	10.1 ±8.6	3.3 ±5.3	0.8 ±2.1	0.1 ±1.1	1.3 ±3.1	0.6 ±2.9	1.6 ±6.0
> 30 persons per km² (mean canopy cover 10%)	0.2 ±4.2	1.8 ±7.0	2.5 ±3.8	0.8 ±2.9	-1.1 ±1.4	-1.6 ±3.6	-1.0 ±3.6	0.1 ±3.4
Cropland (mean canopy cover 11%)	0.9 ±4.6	2.6 ±6.7	4.1 ±4.4	3.5 ±2.8	-1.0 ±1.3	2.0 ±2.7	-1.2 ±2.9	1.5 ±4.3
Grass/shrub savanna (mean canopy cover 9%)	2.5 ±5.4	8.9 ±8.8	5.1 ±5.5	1.3 ±3.3	-0.1 ±1.6	1.8 ±3.4	0.0 ±3.7	0.9 ±4.2
Woodland (mean canopy cover 15%)	3.9 ±7.3	7.1 ±7.4	6.0 ±5.8	1.7 ±3.5	-0.6 ±1.8	1.4 ±3.3	-1.9 ±6.8	3.1 ±9.4

Woody cover trends at Sahel scale

Overall, the mean predicted woody cover (%) (2000-2014) averages (±standard deviation) to 7.6 ±8.4 (Fig. 5a, Table 2). There is a gradient with increasing woody cover from north to south following the mean annual rainfall, which is expected (Sankaran *et al*., 2005). Woody cover varies between the Sahelian countries (Table 2, Fig 5a), with Senegal having the highest mean woody cover but also the highest variations (20.4 ±14.8) and Niger the lowest cover and the lowest variations (3.6 ±3.2). These differences can be mostly explained by the north south gradient, prevailing land cover and soil fertility, with large parts of Niger and Mali located in the sparsely vegetated northern fringe of the Sahel, while Senegal and Nigeria include woodlands and forest reserves (Fig. 2).

Trend analysis of predicted woody cover from 2000-2014 shows an increment of 1.7 ±5.0 (woody cover %) over the period across the Sahel (Fig. 5b). A pattern according to population density and land cover/use (Table 2) can be observed. Savannas and woodland have an overall distinct increment in woody cover (2.5 ±5.4 and 3.9 ±7.3). Whereas both land cover types show strong positive changes in sparsely populated areas (3.1 ±5.9 and 3.5 ±7.9), this trend is strongly attenuated but still positive in densely populated areas (0.7 ±4.5 and 1.0 ±5.9). Moreover, regions characterized by dense population are more likely to show a decrease in woody cover (Fig. 5b) with an overall neutral tendency across the Sahel (0.2 ±4.2), as compared to sparsely populated areas with an increase of 2.1 ±4.3. Decreases in woody cover within densely populated areas are mostly located in tiger bush rangeland and forest reserves, whereas no clear change is observed in croplands (0.9 ±3.5). The woodland in Nigeria shows the strongest decrease (-1.9 ±6.8), whereas the sparsely populated areas in Senegal have the highest increase (10.1 ±8.6). The difference between sparsely and densely populated areas (1.8 ±7) is also highest in Senegal. Chad has opposing trends in sparsely (1.3 ±3.1) and densely (-1.6 ±3.6) populated areas, as does Niger (0.1 ±1.1 and -1.1 ±1.4 respectively). Generally, the standard deviations (±) are high, indicating a high spatial variability between and within countries and along the north south gradient.

Figure 5b shows consistent regional trends at Sahel scale: positive in eastern Senegal, western and central Mali as well as in eastern Niger and central Chad, but negative in western and southern Niger, northern Nigeria, western Senegal and southwestern Sudan. The pattern in southern Sudan is heterogeneous and patchy with positive and negative spots. Many patterns are linked to land cover units. For example, the green areas in Mali, Chad and Senegal are wood- and shrubland with a woody cover >15% and dominate in regions of low human population density and protected areas used for grazing purposes. Northern savannas with a very sparse woody cover are characterized by subtle trends below 1% and changes appear in both directions. Woodland in densely populated areas appears mostly negative, for example in Nigeria, Sudan, Niger, but also close to Dakar in Senegal.

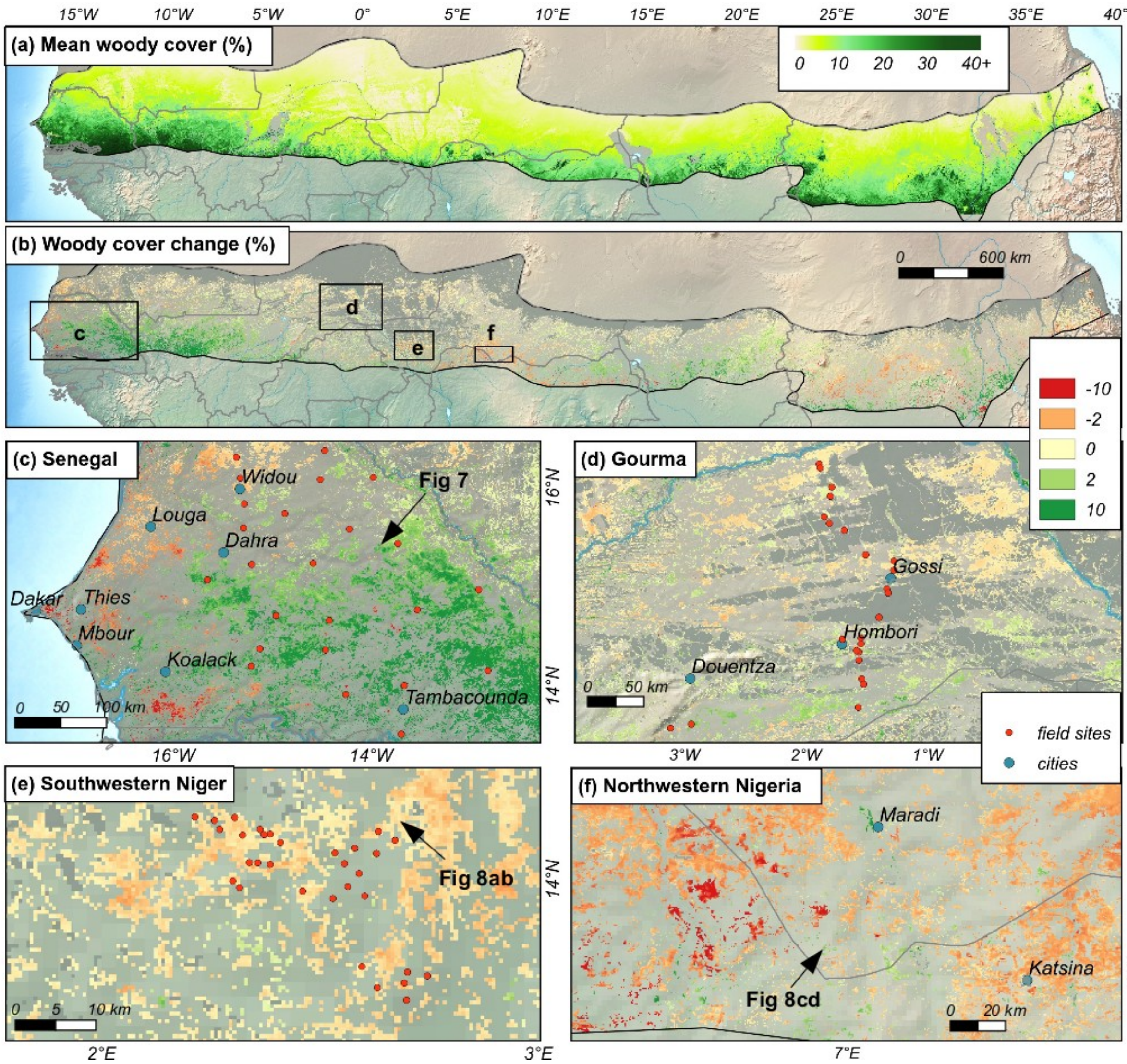

Figure 5 Predicted woody cover changes (2000-2014) in the Sahel: **(a)** Mean woody cover, **(b)** changes of woody cover in the Sahel belt show a heterogeneous pattern, **(c)** in Senegal the east has positive trends and the west negative trends, **(d)** in the Gourma (Mali) trends are very subtle, **(e)** in southwestern Niger negative trends are limited to tiger bush areas, **(f)** in northwestern Nigeria strongly negative spots are observed. Non-significant trends (95% level) and masked wetlands are transparent, masked areas with a mean woody cover below 2% displayed dark gray.

Woody cover trends in Senegal

Large parts of eastern Senegal belong to the silvo-pastoral zone with limited human influence, a low population density and various forest reserves. With favorable rainfall conditions, the woody vegetation has the time and chance to disperse. This is expressed in Table 2, Figure 5c and supplementary material, showing that the EO based estimate of woody cover evolution is increasing substantially between 2000 and 2014 (yet not in the Kooya, western Ferlo area, though lightly populated and within a forest reserve). The densely populated areas in the western parts of Senegal have a rather stable woody cover over this time period. Several negative spots can be seen in proximity to the bigger cities (e.g. Tambacounda, Dakar, Thies, Mbour and Louga) and in the Saloum (Fig. 5c).

Woody cover trends in the Gourma region of Mali

Mean woody cover in the Gourma is low (around 3%) and large areas of very sparse woody vegetation, especially over the shallow soils on rocky and ferricrete outcrops, stand below the 2% threshold for trend assessment (Fig 5a). On sandy soils, trends in predicted cover are subtle, negative over the sand dunes fringing the Niger river in the north and north east, and also further south around Gossi and Hombori. Trends are slightly positive on sandy soils in the north (away from the Niger river), and in the Seno dune system (away from cropland in the south) (Fig. 5d). The trend of predicted woody cover in fine textured soils along wadies and in depressions are either neutral or positive, even close to towns such as Gossi, Hombori and Douentza.

Woody cover trends in southwestern Niger

Whereas the sparsely populated rangeland regions in eastern Niger (away from the Nigeria border) show more neutral and positive trends in predicted woody cover, the more densely populated areas in southwestern Niger and close to the Nigeria border are characterized by significant decreasing trends (Fig. 5e). Here, both rangeland and cropland areas are classified as densely populated, but the decrease in predicted woody cover is more pronounced in rangeland areas including the tiger bush of the ferricrete plateau, while cropland woody cover remain mostly unchanged, or sometimes positive (Fig. 5e and supplementary material). Woody cover trends also affect the mosaic of crop and fallows on sandy soils in directions depending on topographic position: decreasing at top slopes, while they are stable and locally positive at mid and bottom slopes.

Woody cover trends at the border between Nigeria and Niger

In northwestern Nigeria (state of Zamfara) and southern Niger (Maradi with the forest reserve of Baban Rafi) strongly negative changes of predicted woody cover appear locally, in spite of stable rainfall (Fig. 5f and supplementary material). These negative changes are often spatially limited to uncultivated woodland and forest reserves (woody cover around 30%), and suggest selective logging and active land cover transition from open woodland to agrarian parkland (Fig. 6). Over the 15 year period, an average loss of 5.4% woody cover in the Zamfara and Baban Rafi forests is observed.

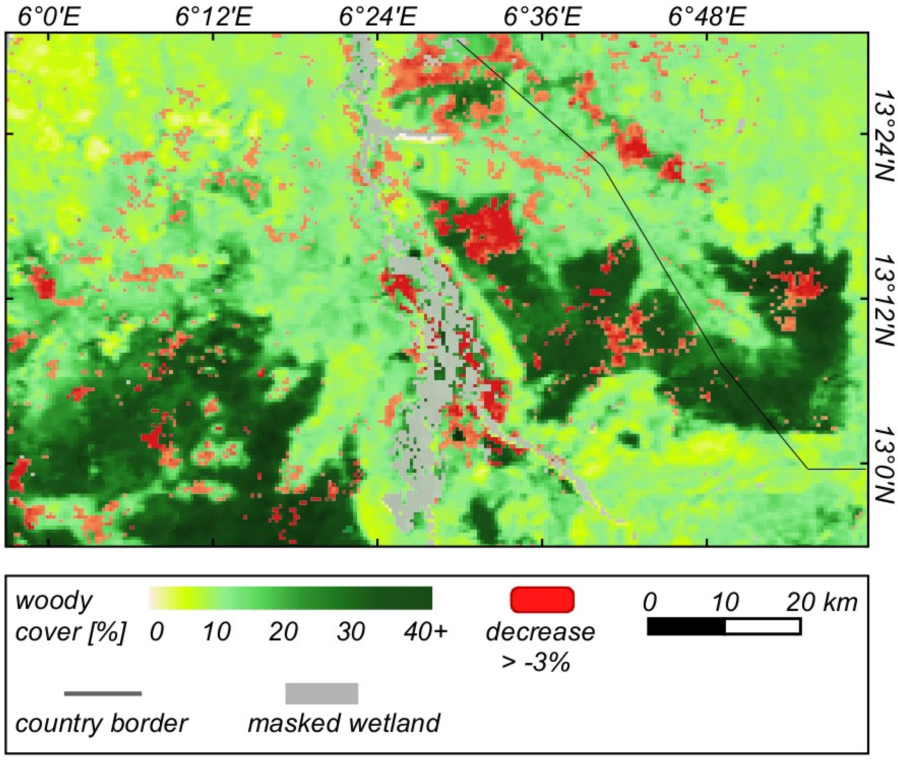

Figure 6 A decreasing woody cover is an indication for selective logging and encroachment of cultivated areas in northwestern Nigeria/southern Niger**.** On the right the Baban Rafi forest reserve in Niger, on the left the top north of the Zamfara reserve in Nigeria, Dumburum sector. Only woody cover decrease higher 3% is shown.

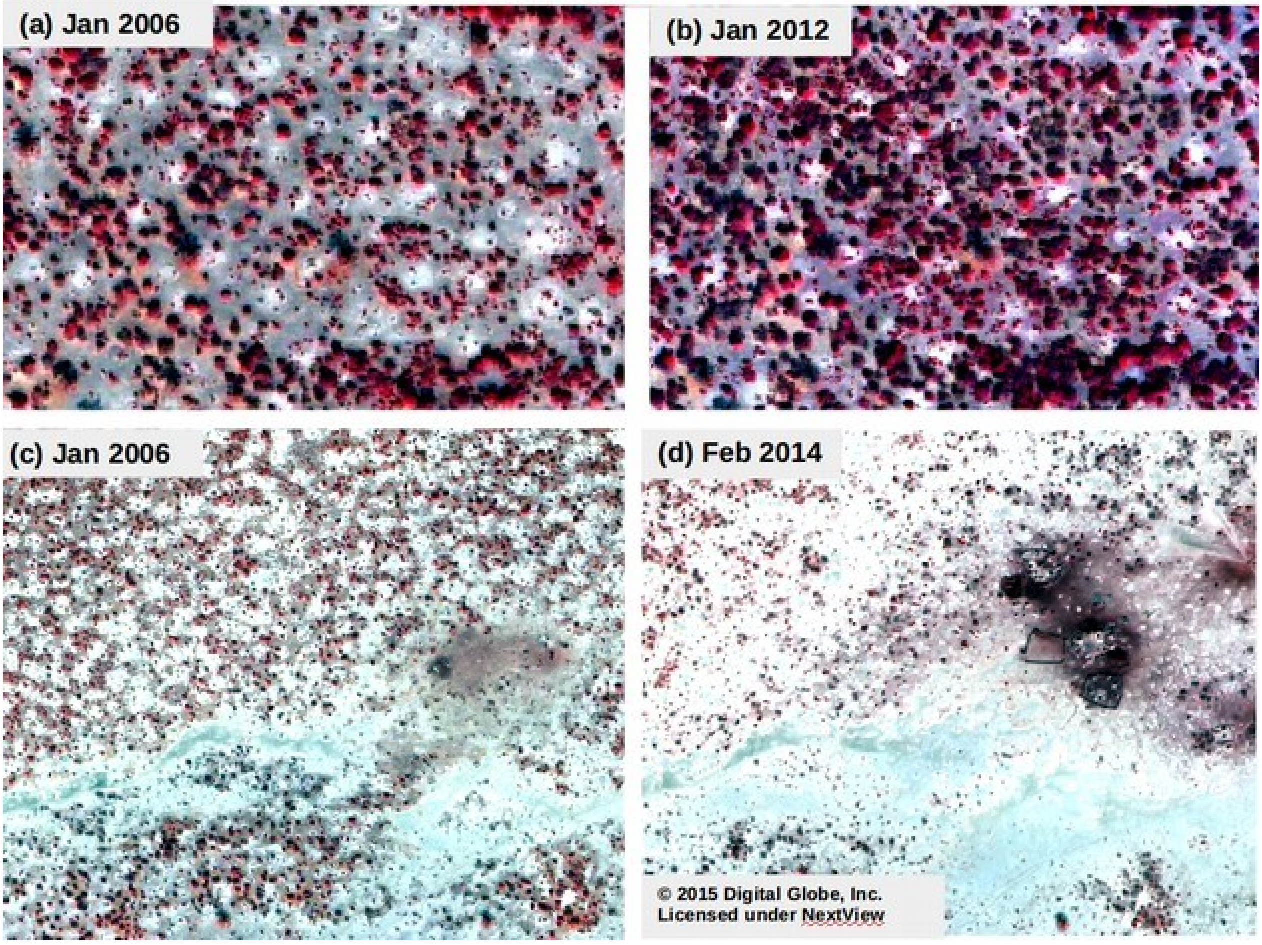

Figure 7 Woody cover trends in shrublands of Senegal captured by high spatial resolution imagery. (a+b) Intensification of woody plant density (red color) is observed. (c+d) Thinning of the woody strata around a Pular settlement (characterized by rapid expansion between 2006 and 2014). The location of the images is shown in Figure 5.

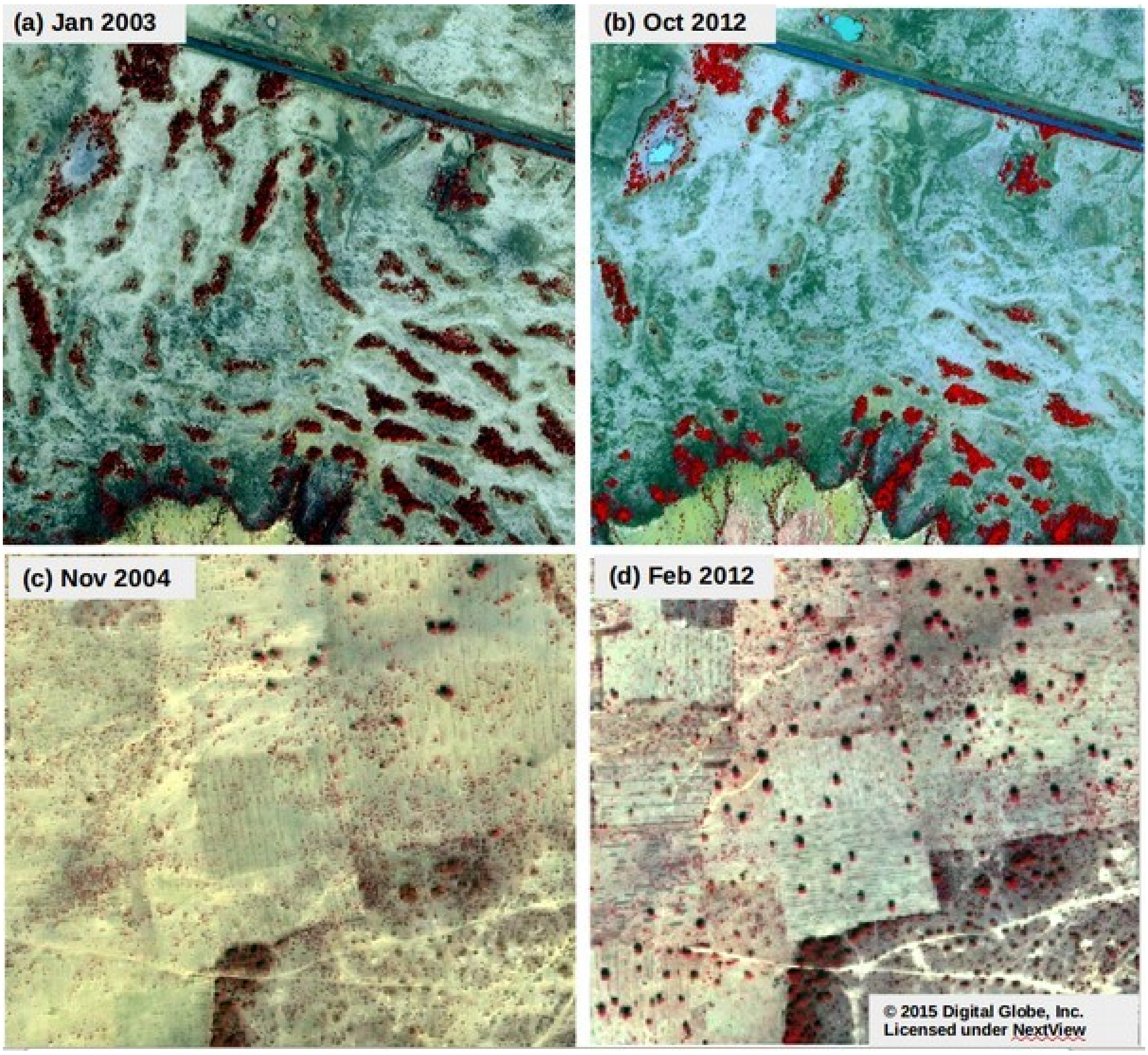

Figure 8 Opposing woody cover trends in Niger and Nigeria. (a+b) The tiger bush rangelands in Niger show a steady decrease in woody plants between 2003 and 2012. The proximity to a road facilitates the transport of fuel wood to nearby towns. (c+d) Agroforestry and sustainable management leads to an increase of woody plants in the farmer's fields in the border region of Southwest Niger and Northern Nigeria. The location of the images is shown in Figure 5.

Discussion

Uncertainties and the impact of rainfall

Many studies, based on coarse resolution EO data, have found that the Sahel is greening, but translating this into trends in well-defined vegetation properties has proven to be difficult (Mbow *et al*., 2015; Herrmann and Tappan 2013). This study shows that woody cover has increased on average for the Sahel, and this contributes significantly to the observed greening, being in line with the findings of Kaptué *et al*. (2015) and Brandt *et al*. (2015). The applied methodology is, however, based on several assumptions and involves choices which may introduce uncertainties. Firstly, it uses the greenness intensity of the foliage of woody plants to derive woody cover. This is based on the assumption that the woody cover has only one layer. Secondly, it is assumed that meaningful and linear trends may be observed over a time period of 15 years. Many natural and anthropogenic factors, including short-term variations in rainfall, browsing pressure and burning practices, may cause short-term variations in foliage density, introducing uncertainties in the identification of slow, longer-term trends in woody cover (Broich et al., 2014). Moreover, trends may not be linear, and die off events and trend reversals were not detected with the proposed analyses. Thirdly, the procedure for identifying woody cover attempts to attenuate these effects by using wet season peak values of NDVI as a proxy for the rainfall conditions in order to correct the dry season NDVI for rainfall-controlled fluctuations. Whereas 67% of the pixels in the Sahel belt could be corrected, the statistical relation between rainfall and woody plants does not exist for the remaining 33%, leading to uncertainty in these areas (map shown in supplementary material). Several reasons may be given for such decoupling of dry season NDVI from peak wet season NDVI, including irregular burning and the reliance of woody plants on ground water (e.g. gallery forests, flooded plains). Yet qualitative assessments of the maps produced indicate that uncertainties are local and mostly affect particular edaphic niches and the results presented are in line with existing field studies (Brandt *et al*., 2014; Brandt *et al*., 2015; Hiernaux *et al*., 2009a; Hof *et al*., 2003; Ichaou, 2009).

Sahel-wide trends in woody cover

The overall trend in woody cover is over the 15 year period is positive, as shown in Figure 5b. The detected trends are caused by changes in foliage density, canopy increment (accompanied by wood mass, basal area, carbon storage, etc) and woody population density. The trends may be assumed to be influenced by a range of external, biophysical as well as anthropogenic factors, including medium-term rainfall change, increase in CO_2-concentration in the atmosphere, clearing, cutting, browsing and burning. The rainfall conditions over the study period show no major trends for Sahel as a whole (supplementary material), yet a globally raising atmospheric CO_2 level may contribute to the trend, favoring the growth of C3 plants including woody species (Donohue *et al*., 2013). Our findings (and in particular Table 2) show clearly that the increase in woody cover is pronounced in areas with low population density, and in particular in grass/shrub savanna and woodland. This points to anthropogenic factors as the explanation of the observed differences in trends and suggests that the Sahel woody cover is able to recover relatively rapidly, when natural factors allow it, and anthropogenic pressures are low enough (Woomer *et al*., 2004). With the possibility of higher rainfall and increasing CO_2-concentration, the Sahel thus may have potential for increased woody cover despite high rainfall variability. It is noteworthy that negative hot-spots (e.g. in Senegal, Niger and Nigeria) correspond with areas of a high demand for phytomass (Abdi et al., 2014), i.e. wood cutting and clearing either for fire-wood and construction or clearing for cropping fields. However,woody cover is on average stable or slowly increasing in croplands, which may result from the benefits of combining trees with farming/pastoral practices in that region (Mbow *et al*., 2014), and also pastoral areas (including high stocking rate areas) do mostly show increases in woody cover. Evidences of increased on-farm tree densities as a result of improved land use and management emerged at local scale and trees in farms have shown a steady increase by various studies as a result of many practices such as assisted natural regeneration (Bayala *et al*., 2011).

Site-specific trends

Even though the overall trend is positive, our results show a diverse pattern with areas of a positive change but also areas with loss of woody cover. The high standard deviations shown in Table 1 suggest huge variations within the countries and the need for more local studies. The map of woody cover trends (Figure 5b) for the entire Sahel clearly shows that many site specific deviations from the average Sahel canopy increase can be found, and examples of these are given in Figure 7 and 8. On the Malian Dogon plateau, tiger bush close to Fiko has negative trends, while woody cover in valleys and the narrow faults on the sand stone plateau have positive trends, fields are neutral or positive. This is in line with a field study by Brandt *et al*. (2014) and observations in northern Burkina Faso (Rasmussen *et al*., 2014). The drivers are not limited to rainfall, but also dynamics of water run-off/run-on with an increasing redistribution that may favor woody plants in lowlands to the detriment of the uplands. Furthermore, we have shown the strongly positive trends of the shrubland in eastern Senegal, illustrated in Fig. 7ab, but also the thinning of woody stands can be observed at the vicinity of enlarging settlements (Fi. 6cd). Tiger bush rangelands on ferricrete plateaus in Niger are exploited to provide fuel-wood and charcoal to Niamey and smaller towns along the Niger River (Fig. 8ab). Also, deforestation is visible in northern Nigeria and southern Niger, penetrating locally into forest reserves or at their fringes. Besides commercial logging, one of the major environmental challenges in northern Nigeria is the expansion of cropping into grazing reserves and forest areas (Hof, 2006; Ichaou, 2009). The main reasons are population growth and the resulting need for farmland. Political changes with increasing decentralization and release of forestry service authority, allowing progressively more clearing of forest reserves, contribute to this development and to the shrinkage of woodlands (Hof *et al*., 2003). Equally, from 1999 to date, the region witnessed massive infrastructure development (roads, dams, irrigation schemes, electricity lines), which also led to cutting-down of many trees. However, once transformed to a farmland, a spreading of woody plants can be observed (Fig 8cd).

Conclusions

Our study paints a varied, yet overall positive, picture of woody cover dynamics in the Sahel over the last 15 years. With respect to the drivers of woody cover change our results show that the overall positive trends are primarily found in areas of low anthropogenic pressure. This demonstrates the resilience of Sahelian ecosystems, as well as the potential of these ecosystems to provide services such as increased carbon storage, if not over-utilized. Many cases of site-specific decreases in woody cover show that a range of different processes, most often associated with a high population density, may threaten the woody vegetation. It is, however, found that established croplands do not generally experience reductions in woody cover, in contrast to what might have been expected.

Taken together, our results provide an unprecedented synthesis of woody cover dynamics in the Sahel. The important message for the woody cover recovery in large areas challenges the mainstream paradigm of irreversible land degradation or desertification in the Sahel (Herrmann and Tappan, 2013) – Mortimore *et al*. (2001) describe the Sahel systems as 'unstable but resilient'. The assertion of the vicious cycle of the Sahel crisis seems to be replaced by an emerging theory of an adaptive cycle (Rasmussen and Reenberg, 2012) that points to many instances of recovery. Most studies imply that this variability is driven by precipitation, but adding the human dimension and land use gives more insights on the spatial changes to the observed trend. To increase our understanding of the trends and the drivers behind the observed behavior, detailed studies of the processes involved are required. Further, our findings may serve to validate outputs from ecosystem modeling, in order to improve our understanding of the effects of increases in CO_2concentration and climate change on Sahelian ecosystems and their role in the carbon cycle.

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Figure captions:

Figure 1 Methodological work-flow including ground observations and EO data for assessing changes in the woody cover of the Sahel.

Figure 2 Overview of the Sahel belt. (a) Location of the ground monitoring sites in Senegal, the Gourma region in Mali and southwestern Niger. Rainfall delineations (150-300 mm, 300-500 mm, 500-700 mm) are based on annual average precipitation (African Rainfall Climatology Version 2 1983–2013). Land cover is Globeland30 aggregated to 500 m. (b) Population density map is based on the African Population Database (Nelson, 2004) for the year 2000.

Figure 3 Adjusting *in situ* woody cover: (a) DSI (dry season NDVI corrected for inter-annual fluctuations) is compared against the woody cover measurements before and (b), after adjusting the *in situ* woody cover to the dry season foliage density.

Figure 4 Woody cover predictions: **(a)** Predicted woody cover is compared with observed woody cover for all 77 ground sites and 178 *in situ* woody cover measurements. (b) Linear trends in woody cover (woody cover (%) year^{-1}) from 19 field sites in Senegal are compared against the trends predicted from MODIS dry season NDVI (only 19 of the 77 field sites provide continuous data and can be used for trend analysis).

Figure 5 Predicted woody cover changes (2000-2014) in the Sahel: **(a)** Mean woody cover, **(b)** changes of woody cover in the Sahel belt show a heterogeneous pattern, **(c)** in Senegal the east has positive trends and the west negative trends, **(d)** in the Gourma (Mali) trends are very subtle, **(e)** in southwestern Niger negative trends are limited to tiger bush areas, **(f)** in northwestern Nigeria strongly negative spots are observed. Non-significant trends (95% level) and masked wetlands are transparent, masked areas with a mean woody cover below 2% displayed dark gray.

Figure 6 A decreasing woody cover is an indication for selective logging and encroachment of cultivated areas in northwestern Nigeria/southern Niger**.** On the right the Baban Rafi forest reserve in Niger, on the left the top north of the Zamfara reserve in Nigeria, Dumburum sector. Only woody cover decrease higher 3% is shown.

Figure 7 Woody cover trends in shrublands of Senegal captured by high spatial resolution imagery. (a+b) Intensification of woody plant density (red color) is observed. (c+d) Thinning of the woody strata around a Pular settlement (characterized by rapid expansion between 2006 and 2014). The location of the images is shown in Figure 5.

Figure 8 Opposing woody cover trends in Niger and Nigeria. (a+b) The tiger bush rangelands in Niger show a steady decrease in woody plants between 2003 and 2012. The proximity to a road facilitates the transport of fuel wood to nearby towns. (c+d) Agroforestry and sustainable management leads to an increase of woody plants in the farmer's fields in the border region of Southwest Niger and Northern Nigeria. The location of the images is shown in Figure 5.

Table 1 Dominance distribution of iconic woody species across the bioclimatic sub-zones of the Sahel (species named after Arbonnier, 2004) with indication of the foliage phenology: evergreen renewing foliage at the onset of the dry or wet season, deciduous with foliage duration either short, medium, long or reversed with foliage only during the dry season. A complete table with potentially dominant species is found in the supplementary material.

Sahel bioclimatic zones		**Northern**			**Central**			**Southern**		**Phenological behavior**
isohyets (mm)	150			300			500		700	
woody cover (%)		2			6			15		
Salvadora persica	*	*								Evergreen (dry season)
Maerua crassifolia	*	*	*							Evergreen (dry season)
Euphorbia balsamifera	*	*	*	*	*					Short deciduous
Acacia tortilis raddiana	*	*	*	*	*					Long deciduous
Acacia ehrenbergiana	*	*	*	*	*					Medium deciduous
Commiphora africana	*	*	*	*	*	*				Short deciduous
Leptadenia pyrotechnica	*	*	*	*	*	*				Evergreen (dry season)
Calotropis procera	*	*	*	*	*	*	*			Evergreen (dry season)
Balanites aegyptiaca	*	*	*	*	*	*	*	*	*	Evergreen (dry season)
Ziziphus mauritiana	*	*	*	*	*	*	*	*	*	Medium deciduous
Acacia nilotica	*	*	*	*	*	*	*	*	*	Long deciduous
Boscia senegalensis	*	*	*	*	*	*	*	*	*	Evergreen (dry season)
Acacia seyal		*	*	*	*	*	*	*	*	Short deciduous
Combretum micranthum			*	*	*	*	*	*	*	Short deciduous
Faidherbia albida			*	*	*	*	*	*	*	Reversed deciduous
Guiera senegalensis			*	*	*	*	*	*	*	Long deciduous
Acacia senegal			*	*	*	*	*	*	*	Short deciduous
Piliostigma reticulatum				*	*	*	*	*	*	Evergreen (wet season)
Pterocarpus lucens				*	*	*	*	*	*	Medium deciduous
Anogeissus leiocarpus				*	*	*	*	*	*	Medium deciduous
Combretum glutinosum					*	*	*	*	*	Evergreen (wet season)
Adansonia digitate					*	*	*	*	*	Long deciduous
Sclerocarya birrea					*	*	*	*	*	Medium deciduous
Pterocarpus erinaceus								*	*	Medium deciduous
Prosopis Africana								*	*	Long deciduous
Bombax costatum								*	*	Short deciduous
Vitellaria paradoxa								*	*	Evergreen (wet season)

Table 2 Mean woody cover (%) and significant ($p<0.05$) change in woody cover (%) (2000-2014), averaged by countries and classes. The mean woody cover per class (first column) is shown in brackets. Mean and standard deviation are given. Only the areas inside of the Sahel belt are considered. Striking differences can be found between densely and sparsely populated areas.

	Sahel	**Senegal**	**Mali**	**Burkina Faso**	**Niger**	**Chad**	**Nigeria**	**Sudan**
Mean woody cover (%)	7.3 ±8.4	20.4 ±14.8	6.4 ±8.3	8.5 ±5.9	3.6 ±3.2	7.2 ±6.1	11.8 ±6.4	8.7 ±7.7
Change in woody cover (%)								
Entire area (mean cover 8%)	1.7 ±5.0	7.2 ±7.3	3.5 ±5.0	1.2 ±3.2	-0.3 ±1.4	1.4 ±3.1	-0.8 ±3.8	1.1±4.4
< 10 persons per km² (mean canopy cover 6%)	2.1 ±5.2	10.1 ±8.6	3.3 ±5.3	0.8 ±2.1	0.1 ±1.1	1.3 ±3.1	0.6 ±2.9	1.6 ±6.0
> 30 persons per km² (mean canopy cover 10%)	0.2 ±4.2	1.8 ±7.0	2.5 ±3.8	0.8 ±2.9	-1.1 ±1.4	-1.6 ±3.6	-1.0 ±3.6	0.1 ±3.4
Cropland (mean canopy cover 11%)	0.9 ±4.6	2.6 ±6.7	4.1 ±4.4	3.5 ±2.8	-1.0 ±1.3	2.0 ±2.7	-1.2 ±2.9	1.5 ±4.3
Grass/shrub savanna (mean canopy cover 9%)	2.5 ±5.4	8.9 ±8.8	5.1 ±5.5	1.3 ±3.3	-0.1 ±1.6	1.8 ±3.4	0.0 ±3.7	0.9 ±4.2
Woodland (mean canopy cover 15%)	3.9 ±7.3	7.1 ±7.4	6.0 ±5.8	1.7 ±3.5	-0.6 ±1.8	1.4 ±3.3	-1.9 ±6.8	3.1 ±9.4